REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31-01-2000

2. REPORT TYPE
Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Solar Concentration Inflation Control System

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Lester, D.M.; Wassom, S.R.; Hancey, B.D.; Siefkas, P.L.

5d. PROJECT NUMBER
1011

5e. TASK NUMBER
00VA

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

Thiokol Propulsion
P.O. Box 707, M/S 200
Brigham City UT 84302-0707

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-2000-024

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	A		Michael Holmes
					19b. TELEPHONE NUMBER *(include area code)* (661) 275-5615

AIAA 2000-1571

Solar Concentrator Inflation Control System

D. M. Lester, S.R. Wassom, B. D. Hancey, and
P. L. Siefkas
Thiokol Propulsion
Brigham City, Utah

41st AIAA/ASME/ASCE/AHS/ASC
Structures, Structural Dynamics, and Materials
Conference and Exhibit
AIAA Space Inflatables Forum

April 3 - 6 2000 / Atlanta GA

AIAA-2000-1571

SOLAR CONCENTRATOR INFLATION CONTROL SYSTEM

D.M. Lester, S.R. Wassom, B. D. Hancey, P. L. Siefkas
Thiokol Propulsion*
Brigham City, Utah

ABSTRACT

An important component of any space-rated inflatable structure is the inflation system. Precise control of the inflation pressure during deployment and operation prevents unwanted dynamic responses in the structure. This paper describes the development and operation of an inflation control system used during low pressure (5E-5 torr) testing of an inflatable solar concentrator. An advanced rapid prototyping method was used to go from concept to vacuum chamber deployment in 6 weeks. A block diagram of the dynamic system was graphically constructed and the closed-loop controller was designed and simulated. This model was then automatically converted to optimized C code. This code was compiled, linked, downloaded, and run in real time on a special Pentium-based PC. Connections between the real hardware and the simulation program were formed and edited graphically. A user-built interactive animation interface on the host PC enabled the user to monitor all outputs and change controller parameters "on the fly" with graphical sliders, buttons, and switches. The inflation control system uses special logic to send out very small pulses of gas during inflation. This slow inflation dramatically reduced the violent effects of gas expansion under vacuum conditions. The controller proved successful in controlling both torus and concentrator pressures to pre-set values during a 6 hour thermal vacuum test in a large NASA vacuum chamber.

INTRODUCTION

Inflatable solar concentrators are important components of solar thermal propulsion (STP) systems. STP uses the sun's energy to heat a low molecular weight fuel such as hydrogen. The thermal energy stored in the hot fuel is then converted to kinetic energy by expansion through a diverging nozzle. This results in a high efficiency (800 – 1,000 sec Isp) low thrust (2-10 lbf) propulsion system[1]. Spacecraft powered using STP systems have been proposed for orbital transfer, interplanetary, and other delta velocity missions.[2] Figure 1 shows a conceptual view of a solar thermal rocket on orbit, featuring inflatable solar concentrators supported by inflated and rigidized struts.[3]

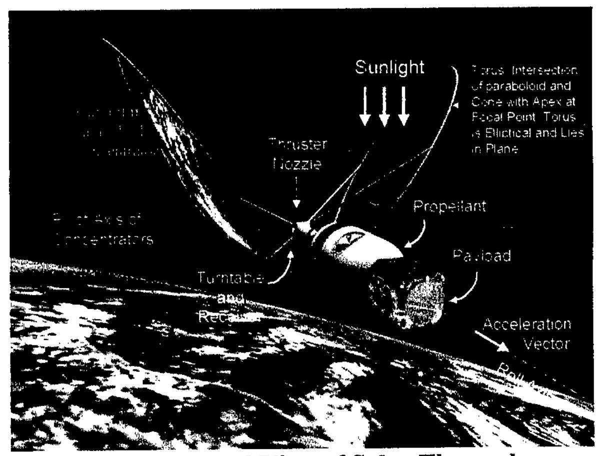

Figure 2. Conceptual View of Solar Thermal Propulsion

Inflatable solar concentrators can be packaged more efficiently than rigid concentrators of equal power. Figure 2 shows a volumetric

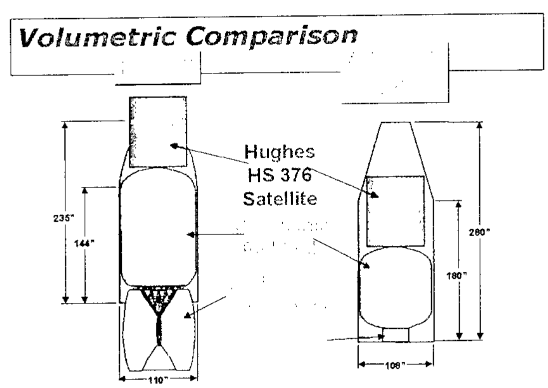

Figure 1. Packaging Comparison of Inflatable and Rigid Concentrators

comparison for a solar orbital transfer vehicle using equal power inflatable and rigid concentrators. As can be seen from this illustration, the inflatable concentrators can be packaged easily within available launch vehicle fairings, whereas the rigid concentrator requires a much larger and more expensive launch vehicle to fly the same payload.

An inflation control system (ICS) capable of controlled on-orbit deployment and rigorous management of component inflation pressures is essential for mission success. In this paper, the design, fabrication, and proof-of-concept demonstration of an ICS in a large vacuum chamber will be described.

DESIGN AND FABRICATION

Thiokol developed the ICS using an advanced rapid prototyping methodology based on the MATRIXx family of hardware and software tools (Figure 3).[4] The advantages of this rapid prototyping

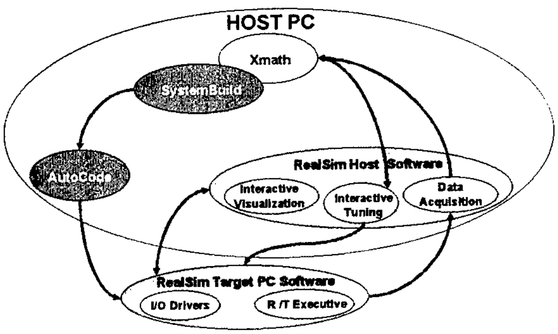

Figure 3. MATRIXx Family

approach, sometimes known as "build-a-little, test-a-little," include: 1) virtually no software written by hand, 2) substantial savings of time and money in code generation, 3) short iteration cycles result in early problem identification and solution.

Figure 4 provides a schematic of the STP inflation system. A mathematical model of this system was created using the SystemBuild feature of MATRIXx. Figures 5, 6, and 7 illustrate 3 levels of

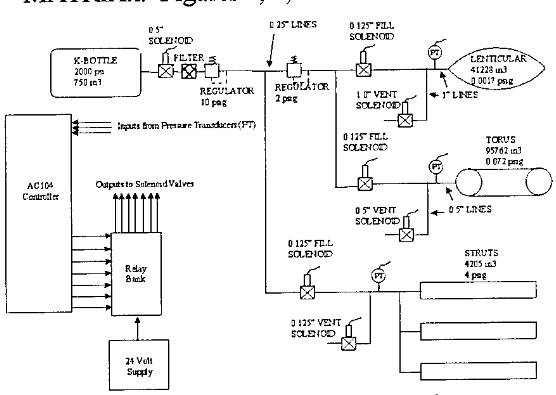

Figure 4. Schematic of STP Inflation System

hierarchy in the SystemBuild math model of the STP inflation system.

Figure 5 shows the top-level super-block, consisting of the AC104 computer (functioning as the controller) and the plant (system to be controlled).

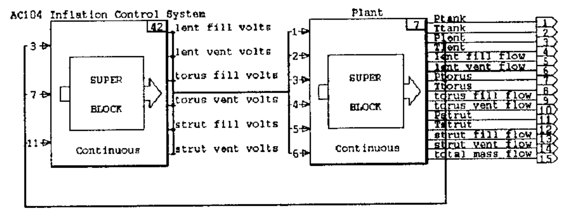

Figure 5. Top-Level Model of STP Inflation System

Figure 6 is the second level, an expanded view of the plant super-block, which contains the volume filling and venting calculations for the various volumes in the system: supply tank, struts, torus, and lenticular.

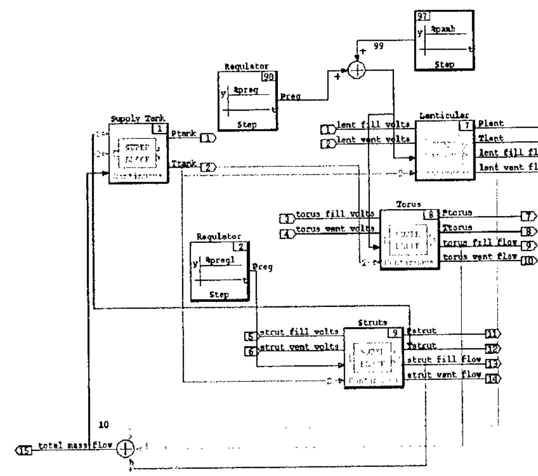

Figure 6. Plant Model

Figure 7 shows the plant model one level deeper into one of the components, the lenticular.

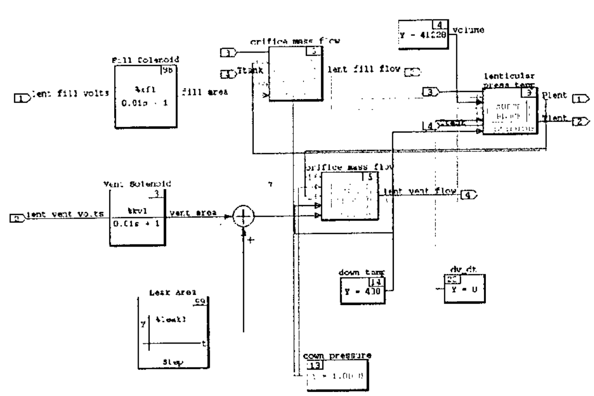

Figure 7. Lenticular Model

(The torus and strut models are similar.) This superblock contains orifice mass flow blocks, a pressure-temperature block, and first-order transfer functions for the fill and vent solenoids. The orifice mass flow super-blocks consist of equations for one-dimensional compressible gas flow, and account for subsonic, sonic, and reverse flow. The inputs are the upstream and downstream temperature and pressure, as well as the effective flow area. Based on these inputs, the mass flow rates in and out of the volume are computed. The pressure-temperature block solves the conservation of mass and energy equations to determine the gas state inside the volume. It takes as inputs the upstream and downstream temperature and pressure, as well as the volume, mass flow rates in and out, and the change in volume with respect to time.

Although this model is capable of handling changing volumes, it was assumed that the component is initially inflated to a pressure above which the volume change is minimal (this pressure is quite small when compared to the desired operating pressure). This constant volume assumption eliminates the need for deriving a complex equation describing the change in volume as a function of pressure and temperature.

Returning to the top level, Figure 8 shows the contents of the early model of the AC-104 acting as the ICS. The commanded pressure schedules for each of the components are generated using waveform blocks. Some way was needed for

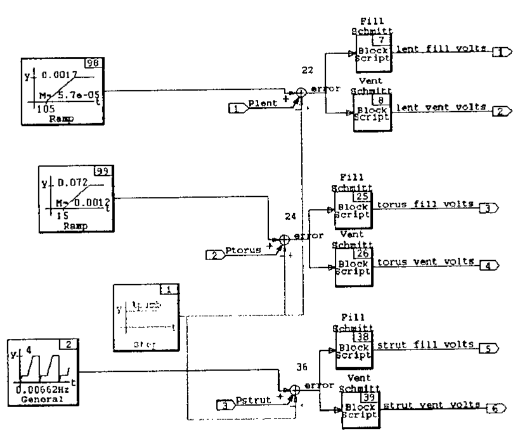

Figure 8. Early Model of AC-104 Controller

converting the error signal (difference between the desired pressure and the actual pressure) into an on/off signal for the solenoids. Two alternatives were investigated, the schmitt trigger and the pulse width modulator (PWM). The schmitt trigger, which is basically a comparator with hysteresis, is the easier of the two to implement. As shown in Figure 9, it simply compares the input to an upper and lower threshold level and determines whether the output should be turned on or off. The PWM (which provides more proportional control than the schmitt

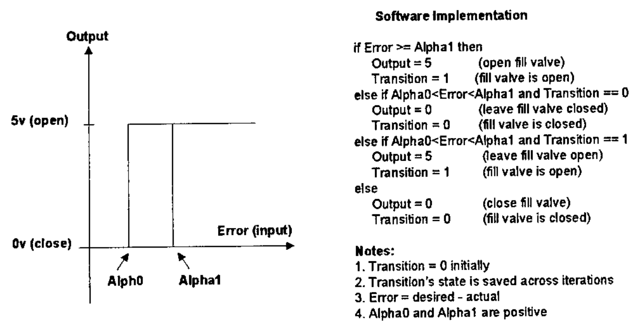

Figure 9. Schmitt Trigger Logic (Filling)

trigger) varies the duty cycle between 0 and 100% based on the value of the input voltage. Since the schmitt trigger provided adequate control, it was selected for further development.

Once this simulation was considered satisfactory, it was run through AutoCode, which automatically converted the graphical model to optimized C code. This code was then compiled, linked, downloaded, and run in real-time on a special Pentium-based PC known as the AC-104 (Figure 10). The component models in the plant (valves, struts, torus, lenticular) were gradually replaced with the real hardware. Connections between the real hardware and the simulation program were formed and edited graphically. Rapid iterations to the controller design were made until an acceptable product was achieved. Each iteration, which only takes a few minutes, generally consists of editing the SystemBuild block diagram, converting to C using AutoCode, and then compiling, linking, downloading, and running on the AC-104.

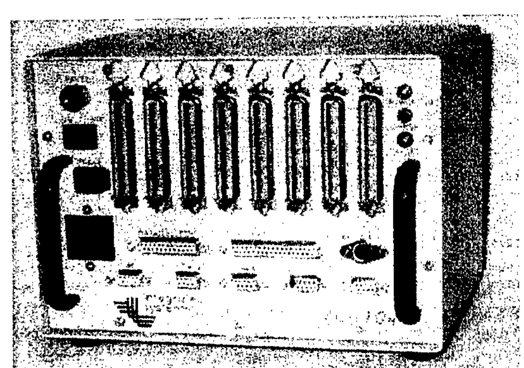

Figure 10. AC-104 Controller

Figure 11 is a graphic representation of the final ICS controller superblock. Within this super block, all components of the completed inflation control system are interfaced. The system runs at 4000 Hz

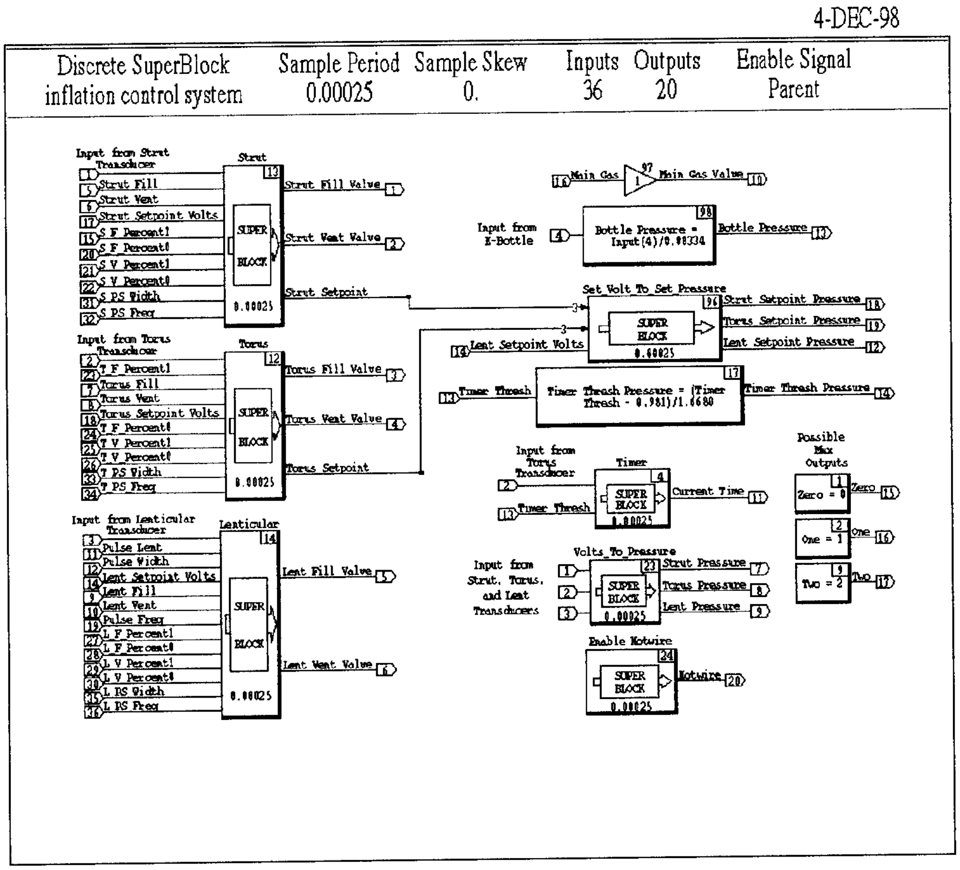

Figure 11. Final ICS Superblock

and contains strut, torus, and lenticular pressure controllers. It also has additional features:

- converts transducer inputs from voltages to pressures
- allows the user to manually control the main gas valve
- energizes the hotwire to enable deployment

The strut controller (one level deeper in the superblock hierarchy) is shown in Figure 12. The structure of the torus controller is virtually the same as the strut controller. The lenticular control differs from the struts and torus in that it is not ramped up to pressure. Because it deals with such low pressures, the pulsed start sequence provides enough pressure in the lenticular to eliminate the need for ramping the pressure up. Only the strut controller is described below to demonstrate the detail used in this design.

The inflation and pressure regulation of the three struts is based on the difference between a desired and an actual pressure. The following paragraphs describe the strut controller blocks in more detail.

Ramp Function*:* This controls the inflation of the struts by ramping them up to an operating pressure of 4 psi over 60 seconds time. The ramp doesn't start until 425 seconds into the inflation sequence, allowing the pulsed start block to run for the first 425 seconds.

Step Functions*:* The step functions serve two purposes. The first, which occurs for the first 425 seconds, keeps the strut vent valve from opening unless the pressure inside the strut exceeds 1.5 psi. The second, which occurs after 425 seconds, adds in the appropriate transducer offset.

Strut Pulsed Start: This block is used to send out small pulses of air to the struts for the first 425 seconds of inflation as long as the pressure stays below 1 psi. This slow initial inflation dramatically reduces the effects of violent gas expansion under vacuum conditions. The user determines the width and frequency of the pulses.

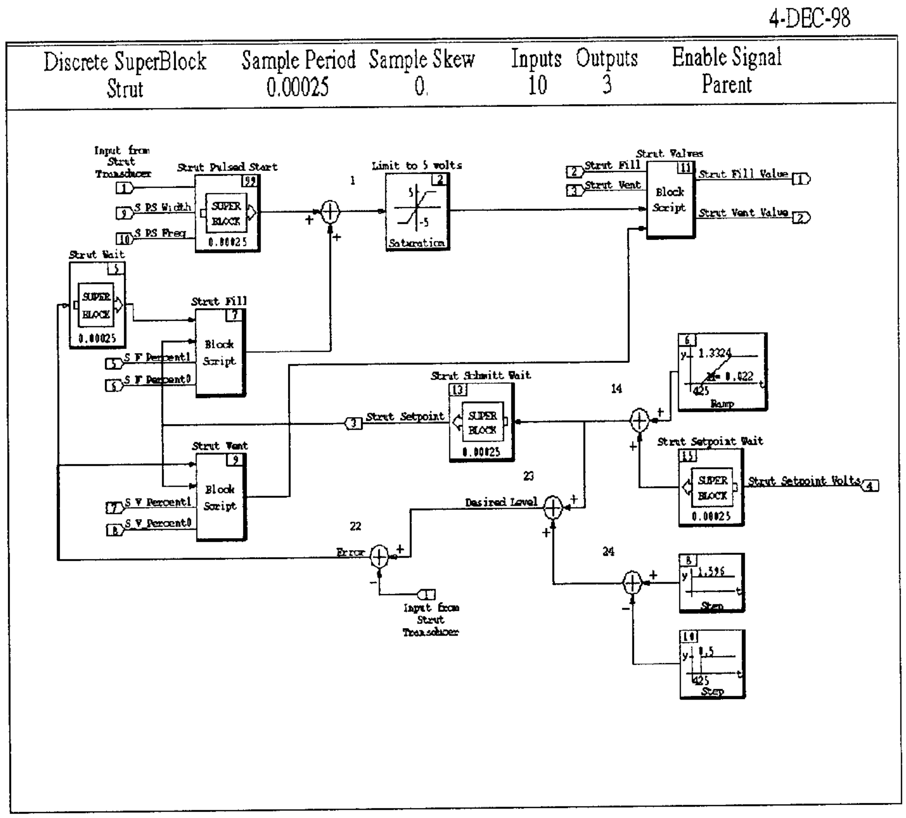

Figure 12. Strut Controller

Strut Wait: The output of this block is forced to zero for the first 425 seconds of operation regardless of the value of the error signal coming in. This in effect disables the strut fill Schmitt trigger until the pulsed start sequence completes.

Strut Schmitt Wait: This block forces the threshold parameters of the Schmitt triggers to a value acceptable for the initial ramping sequence. Once the ramping completes, the thresholds are then computed based on the desired setpoint and percentages input by the user.

Strut Setpoint Wait: This block disables variation of the strut operating setpoint until after the ramp has completed. This is done to eliminate the possibility of a sign swap on the threshold parameters computed in the Schmitt triggers, which would cause the controller to malfunction. Once the ramp has completed, the user can vary the strut setpoint pressure from the initial default of 4 psi.

Strut Fill and Strut Vent: These are the Schmitt triggers used to determine when to open or close the strut fill and vent valves by comparing the incoming error to the threshold parameters. These parameters are computed based on the current operating setpoint and the percentage multipliers input by the user.

Strut Valves: This block determines the operation of the strut fill and vent valves based on the user input. A *zero* forces the valve closed, a *one* forces the valve open, and a *two* forces the valve to do whatever the corresponding Schmitt trigger tells it to do. This block basically allows the user to control the valves either manually or automatically based on their input.

Referring back to the top-level diagram (Figure 11), the Enable Hotwire block provides power to the hotwire for a total of 6 seconds, beginning 4 seconds into the inflation sequence. This hotwire is used to release the containment bag, allowing for deployment of the inflatables. It should be noted that this is the only block in the entire inflation control system that produces output before 5 seconds into the inflation sequence. This allows the hotwire to start heating up before anything begins to inflate. The idea is that the first inflation pulse may help release the containment device if the hotwire is already hot.

The other components shown in the top-level block diagram (Figure 11) are used to display the current supply bottle pressure, whether the user has turned the main gas supply valve on or off, and the timer threshold pressure. This threshold is used

to stall the timer and hence delay the inflation of the lenticular until the torus has reached a user defined pressure.

A user-built interface on the host PC (known as Interactive Animation) was assembled. Figure 13 shows a screen snapshot of this interface. This enables the user to monitor all outputs and change controller parameters "on the fly" with graphical sliders, buttons, and switches.

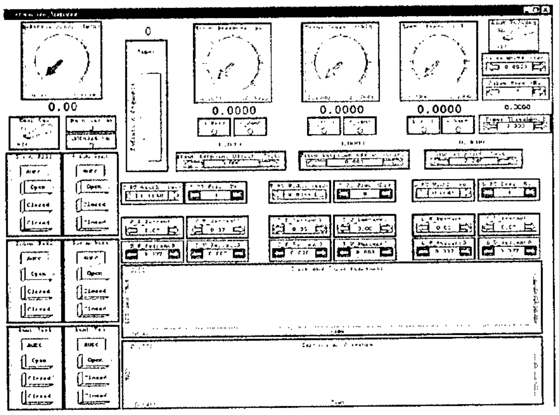

Figure 13 Interactive Animation Interface

It can be used to

- control the individual valves (including the main gas supply valve) and display their current state
- see the state of the hotwire
- see the current pressures in the supply bottle and inflatables
- turn off/on lenticular pulsing and vary the pulse width and frequency of these pulses to compensate for varying lenticular leak rates
- see the current time according to the timer block (including torus pressure threshold delay)
- adjust the operating pressure setpoints
- adjust the timer threshold
- vary the pulsed start and Schmitt trigger parameters.

All user adjustable parameters are limited to ranges acceptable for proper controller operation.

There are two variations of the controller: one for vacuum conditions and the other for ambient pressure conditions. Both consist of the same software superblock components. The only differences involve inflation timing and lenticular pulsing. The pulsed start sequences were not necessary under ambient conditions because gas expansion effects were so much less of a factor. This smaller gas expansion required manual disabling of the lenticular pulsing in order to overcome ambient leak rates. This sped up the inflation process significantly.

TESTING

The ICS was successfully used to inflate and regulate test-scale concentrator 6 (Tsc-6) during low pressure (5E-5 torr) testing at the NASA Glenn Research Center (GRC) Tank 6 during October 1998. Figure 14 shows a photographic view of Tsc-6 in Tank 6. [5] The test included simulated solar flux and cold wall radiation testing. During testing at GRC, only the torus and lenticular were deployed; the struts were rigid and not inflated. The valving, relays, and transducers were located inside the vacuum chamber. The inflation gas supply was provided external to the tank and was hard-plumbed through the chamber wall. The control computer and interactive monitor also remained on the outside of the chamber. The signals of the controller and the responses of the sensors were passed electronically through sealed bulkhead connectors on the chamber wall.

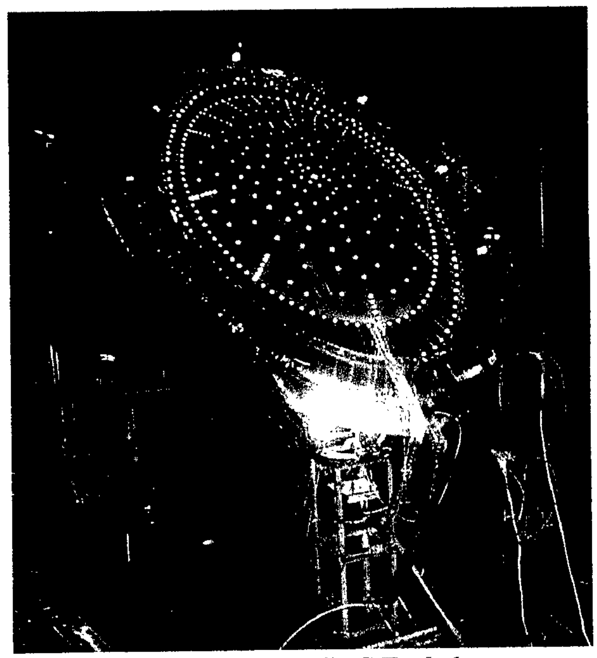

Figure 14. Tsc-6 in NASA GRC Tank 6

During the testing at GRC, it was decided that the ability to manually vent the individual components at any time would be desirable. In order to facilitate this and provide maximum operator control, a series of switches were added to the Interactive Animation interface, allowing the operator to manually control any of the individual fill or vent valves.

The first 300 seconds of inflation were used to expand the torus to shape using short (5 millisecond) pulses of nitrogen at a rate of 5.0 Hz. Using such quick pulses keeps the pressure inside the torus quite low and minimizes the effects of violent gas expansion under vacuum. Once the torus had

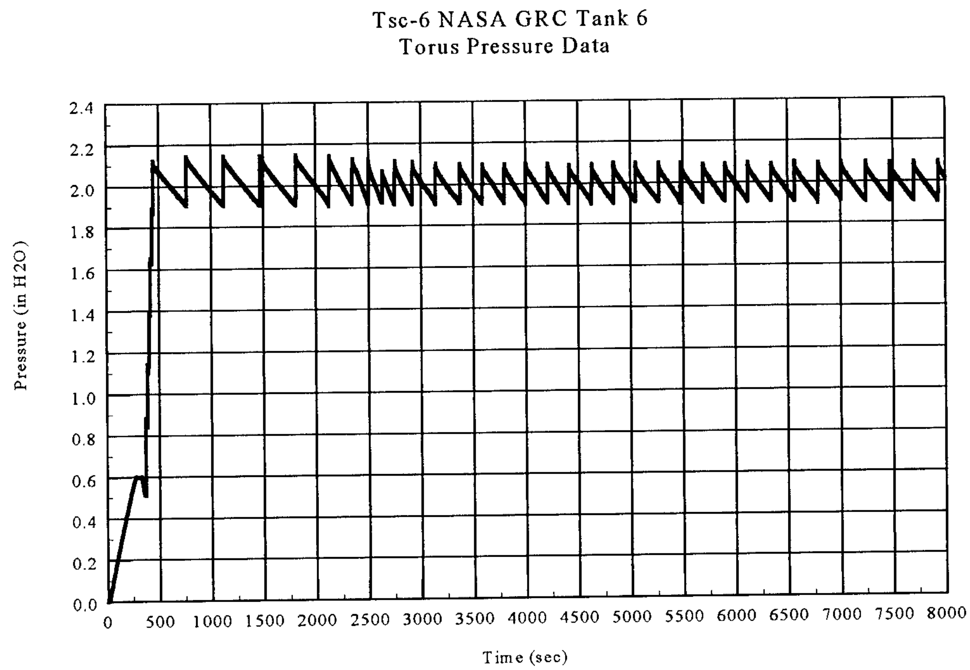

Figure 15. Torus Pressure for First 8000 sec

been extended to shape, the pressure was ramped up to the desired 2.0 inches of water pressure. The pulse commands to the lenticular began at 490 seconds. The pulse width was 4.5 milliseconds with a frequency of 3.0 Hz. These pulses continued until the lenticular reached a pressure of 0.02 inches of water pressure. At that pressure the lenticular had expanded to shape, and the controller switched to an inflation mode of 4 millisecond pulses at a frequency of 12 Hz until the lenticular reached a pressure of

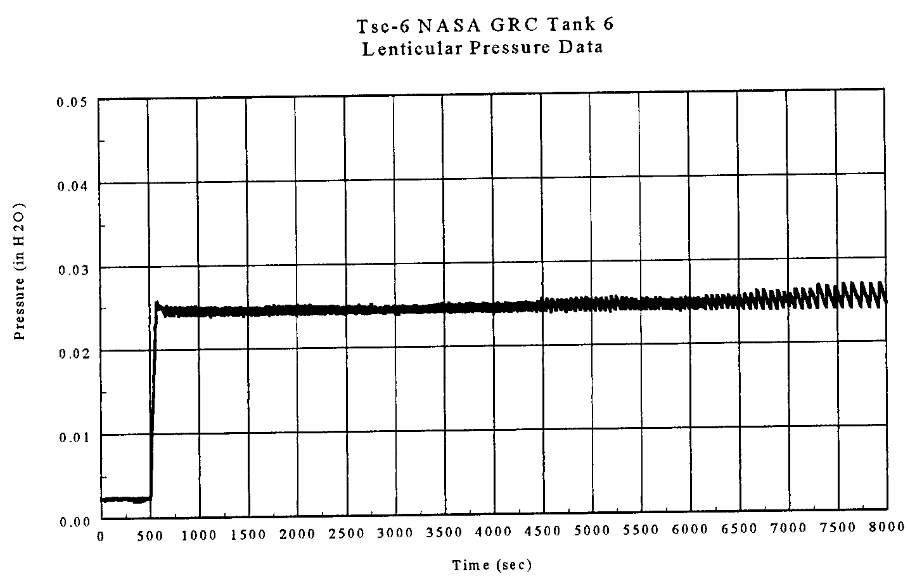

Figure 16. Lenticular Pressure for First 8000 sec

Table 1. Leak Rate			
Time In Minutes	**Test Event**	**Sample Time in Minutes**	**Leak Rate**
0 - 120	Pump Down	18.66 21.11 21.76 24.51	0.042 in.H2O/Min (torus) 0.00174 in.H2O/Min (lenticular) 0.00174 in.H2O/Min (lenticular) 0.042 in.H2O/Min (torus)
120 - 180	#1 Illumination	132.01 133.58 139.70 155.53 159.55 165.25	0.00215 in.H2O/Min (lenticular) 0.00194 in.H2O/Min (lenticular 0.055 in.H2O/Min (torus) 0.048 in.H2O/Min (torus) 0.053 in.H2O/Min (torus) 0.035 in.H2O/Min (torus)
180 - 210	#1 Eclipse	188.9 190.48 198.26	0.048 in.H2O/Min (torus) 0.00208 in.H2O/Min (lenticular) 0.045 in.H2O/Min (torus)
210 - 270	#2 Illumination	231.18 251.22 260.33	0.002152in.H2O/Min (lenticular) 0.047 in.H2O/Min (torus) 0.051 in.H2O/Min (torus)
270 - 285	#2 Eclipse	275.36 278.66	0.00185 in.H2O/Min (lenticular) 0.049 in.H2O/Min (torus)
285 - 305	#3 Illumination	289.18 297.18	0.00173 in.H2O/Min (lenticular) 0.041 in.H2O/Min (torus)
305 --	Shut down & Decay	308.76 319.58 377.73	0.00129 in.H2O/Min (lenticular) 0.031 in.H2O/Min (torus).062 in.H2O/Min (torus) (Final Shut Down)

0.025 inch of water. Figures 15 and 16 show the pressure- time traces of the torus and lenticular, respectively, for the first 8,000 seconds of the test.

To maintain a setpoint pressure in an inflatable concentrator for on-orbit use, the ICS must be able to respond to reasonable leak rate and inflation gas thermal variations induced from earth shadowing on orbit. The leak rates of Tsc-6 measured at 5E-5 torr in GRC Tank 6 on October 22, 1998 are summarized in Table 1. Tsc-6 is a proof-of-concept concentrator and had significantly higher leak rate than that predicted for a space-rated concentrator. This high leak rate demonstrated the robustness of the ICS.

The leak rates were calculated by measuring the difference between the high and low pressures recorded in the lenticular or torus during the pressure control pulses. These values were then divided by the elapsed time. The leak rate is greatest during control periods when fill and vent action takes place to closely regulate the pressure in the torus and lenticular. The torus is maintained at a significantly higher pressure than the lenticular and accounts for about 99% of the gas used. Although pressure leak rates remained nearly constant, a greater mass loss was observed for the colder, denser gas lost during eclipse. By not controlling the pressure in the torus during eclipse, the required mass of gas can be reduced by 36%.

CONCLUSIONS

An inflation system to control the pressures of an inflatable thin film solar concentrator in a space environment has been successfully designed, fabricated, and tested. The Tank 6 test demonstrated that the pressure was maintained to the required levels in a relevant space like environment. The rapid prototyping methodology used promises to be relevant to a wide range of control applications for Solar Thermal Propulsion systems. Miniaturization and space rating of the demonstrated inflation control system are the immediate challenges for future work.

ACKNOWLEDGMENT

The Air Force Research Laboratory, Edwards Air Force Base, CA sponsored this research. Dr. Michael Holmes is the program manager and his support is gratefully acknowledged. The effort was performed as a part of an IHPRPT Demonstrator program, contract #F04611-97-C-0033. Without Tsc-6 provided by SRS Technologies and the Tank 6 vacuum facility provided by NASA Glenn Research

Center, this demonstration would not have happened. We wish to acknowledge the personnel of those organizations for their outstanding contributions to this proof-of-concept demonstration.

REFERENCES

1 Laug, K,. *The Solar Propulsion Concept is Alive and Well at the Astronautics Laboratory,* AFRL, Edwards Air Force Base CA, JANNAF Propulsion Meeting, Cleveland OH, May 1989.

2 Kennedy F., Jacox M., *Mission Applications of an Integrated Solar Upperstage (ISUS).* ASME paper AP0401, 1995

3 Illustration provided by M. R. Holmes Air Force Research Laboratory, Edwards Air Force Base, CA, 1999

4 MATRIX x is software of Wind River Systems Inc.

5 Lester D., *Summary Report Torus Supported Solar Concentrator (Tsc-6) Testing in LeRC Tank 6,* TR11707, Thiokol Propulsion, UT, July 1999